

The opaque plasma and charm

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- motivation, covariant transport theory
- lessons from light sector at RHIC
- results for charm
- open issues: secondary charm, hadronization, coherence

Why heavy quarks?

Provide additional, **heavy** probe of the same partonic medium.

- **question of equilibration**

- heavier quarks are **less likely to equilibrate**

- **parton energy loss**

- perturbative QCD: **weaker interaction** with medium for heavy quarks → **less quenching**

- [Djordjevic, Gyulassy ('03); Dokshitzer, Kharzeev ('01); Wiedemann, Salgado ('03)]

- **quark coalescence**

- extra $c, b, ..$ flavors provide **additional tests**

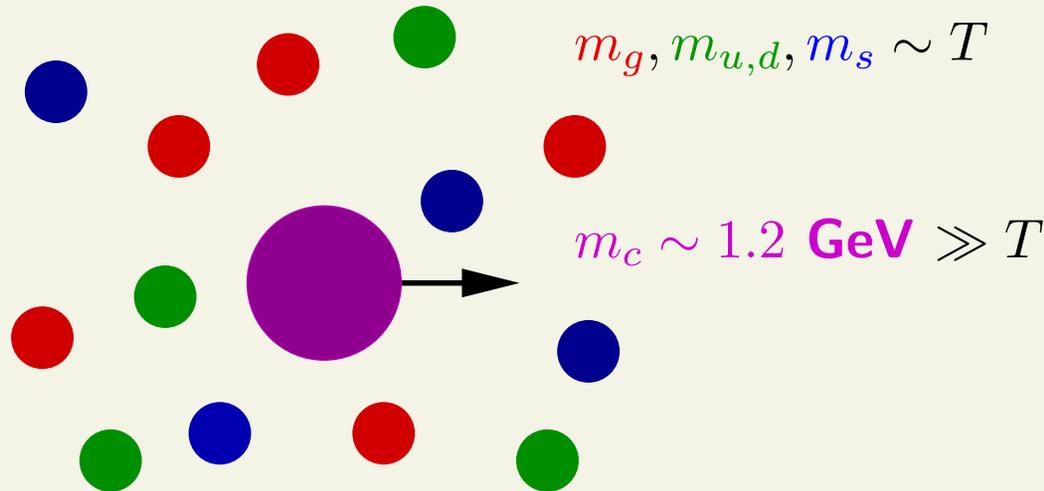
- [Lin, DM ('03); Greco, Ko, Rapp ('04)]

- [● **also: quarkonia ($J/\Psi, \Psi', \dots$) - color screening in medium]**

- [Matsui & Satz, ..., Redlich, Thews, Stöcker, Braun-Munzinger, Rapp, ..., Karsch et al, Asakawa et al,...]

Heavy quark equilibration

~ “Brownian motion” in plasma



$$v \sim \sqrt{T/m}$$

$$p \sim \sqrt{m \cdot T}$$

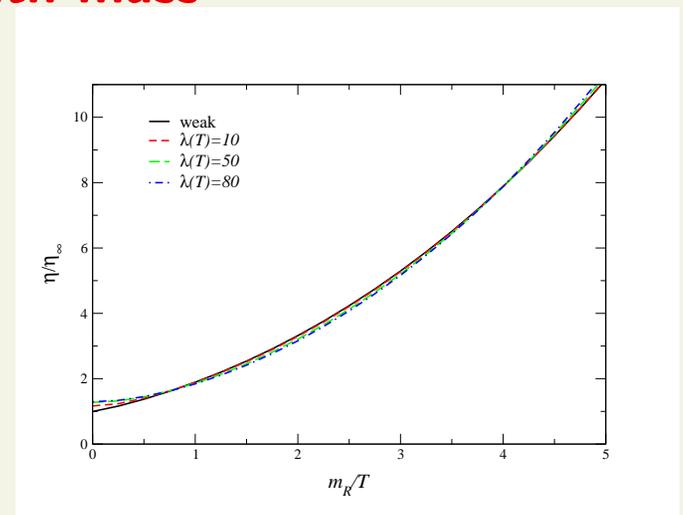
$$N_{coll} \sim p/\Delta q \sim \sqrt{m/T}$$

heavy quarks very heavy \Rightarrow need more collisions to randomize

more quantitative indicator: viscosity grows with mass

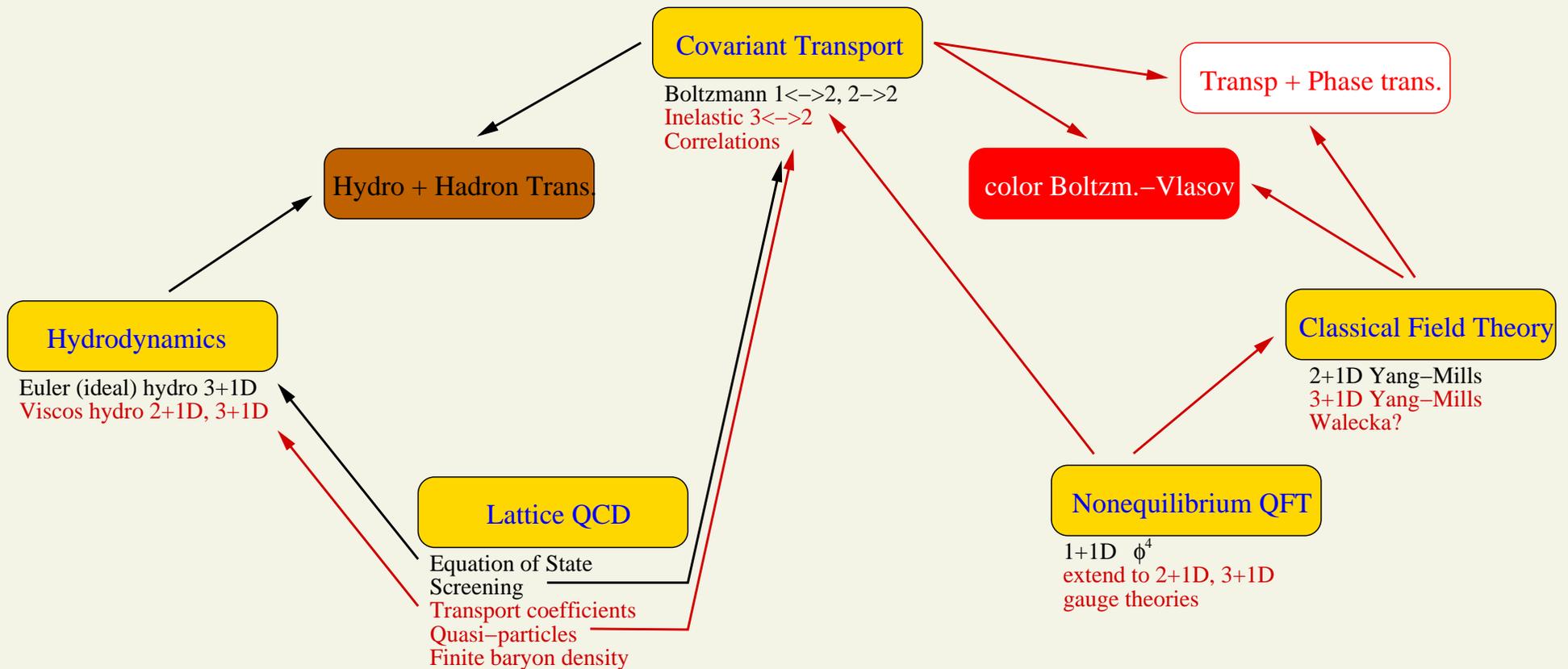
classical kinetic theory: $\eta \approx 0.553\sqrt{mT}/\sigma_{el}$

$O(N)$ model: Aarts & Martinez ('04) \rightarrow



Thermalization study requires **nonequilibrium** approach

→ use covariant transport theory



Quark-gluon kinetic theory

Pang, Zhang, Gyulassy, DM, Vance, Csizmadia, Pratt, Cheng, ...

Incoherent, particle limit of underlying quantum theory (QCD) . Nonequilibrium approach.

local mean free path:

$$\lambda(x) \equiv \frac{1}{\text{cross section} \times \text{density}(x)} \quad \begin{cases} \lambda = 0 & \text{-- ideal hydrodynamics} \\ \lambda = \infty & \text{-- free streaming} \end{cases}$$

Transport opacity: most relevant parameter [DM & Gyulassy NPA 697 ('02)]

$$\chi \equiv \langle n_{coll} \rangle \langle \sin^2 \theta_{CM} \rangle \sim \# \text{ of collisions} \times \text{deflection weight}$$

$$\searrow \sigma^{-1} \int d\Omega \frac{d\sigma}{d\Omega} \sin^2 \theta \equiv \sigma_{tr} / \sigma \rightarrow 2/3 \text{ for isotropic}$$

Boltzmann transport eqn: f_i - quark/gluon phase space distributions

$$p^\mu \partial_\mu f_i(\vec{x}, \vec{p}, t) = \overbrace{S_i(\vec{x}, \vec{p}, t)}^{\text{source}} + \overbrace{C_i^{el.}[f](\vec{x}, \vec{p}, t)}^{2 \rightarrow 2 \text{ (ZPC, GCP, ...)}} + \overbrace{C_i^{inel.}[f](\vec{x}, \vec{p}, t)}^{2 \leftrightarrow 3 \text{ (MPC)}} + \dots$$

highly relativistic case \rightarrow only a few covariant algorithms: ZPC, MPC, Bjorken- τ , ...

Molnar's Parton Cascade (MPC)

Elementary processes: elastic $2 \rightarrow 2$ processes + $gg \leftrightarrow q\bar{q}$, $q\bar{q} \rightarrow q'\bar{q}'$ + $ggg \leftrightarrow gg$

Equation for $f^i(x, \vec{p})$: $i = \{g, d, \bar{d}, u, \bar{u}, \dots\}$

$$\begin{aligned}
 p_1^\mu \partial_\mu \tilde{f}^i(x, \vec{p}_1) &= \frac{\pi^4}{2} \sum_{jkl} \int_2 \int_3 \int_4 \left(\tilde{f}_3^k \tilde{f}_4^l - \tilde{f}_1^i \tilde{f}_2^j \right) \left| \bar{\mathcal{M}}_{12 \rightarrow 34}^{i+j \rightarrow k+l} \right|^2 \delta^4(12 - 34) \quad \swarrow 2 \rightarrow 2 \\
 &+ \frac{\pi^4}{12} \int_2 \int_3 \int_4 \int_5 \left(\frac{\tilde{f}_3^i \tilde{f}_4^i \tilde{f}_5^i}{g_i} - \tilde{f}_1^i \tilde{f}_2^i \right) \left| \bar{\mathcal{M}}_{12 \rightarrow 345}^{i+i \rightarrow i+i+i} \right|^2 \delta^4(12-345) \quad \swarrow 2 \leftrightarrow 3 \\
 &+ \frac{\pi^4}{8} \int_2 \int_3 \int_4 \int_5 \left(\tilde{f}_4^i \tilde{f}_5^i - \frac{\tilde{f}_1^i \tilde{f}_2^i \tilde{f}_3^i}{g_i} \right) \left| \bar{\mathcal{M}}_{45 \rightarrow 123}^{i+i \rightarrow i+i+i} \right|^2 \delta^4(123-45) \quad \swarrow 3 \leftrightarrow 2 \\
 &+ \tilde{S}^i(x, \vec{p}_1) \quad \leftarrow \text{initial conditions}
 \end{aligned}$$

with shorthands:

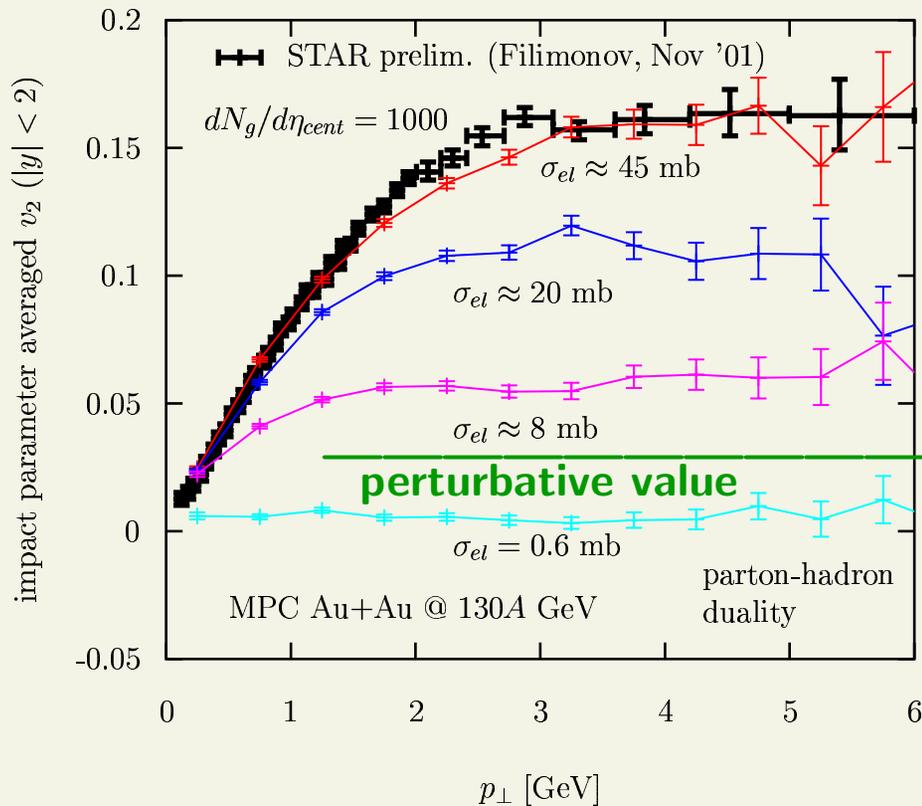
$$\tilde{f}_i^q \equiv (2\pi)^3 f_q(x, \vec{p}_i), \quad \int_i \equiv \int \frac{d^3 p_i}{(2\pi)^3 E_i}, \quad \delta^4(p_1 + p_2 - p_3 - p_4) \equiv \delta^4(12 - 34)$$

Results for light sector at RHIC

Very large opacity at RHIC

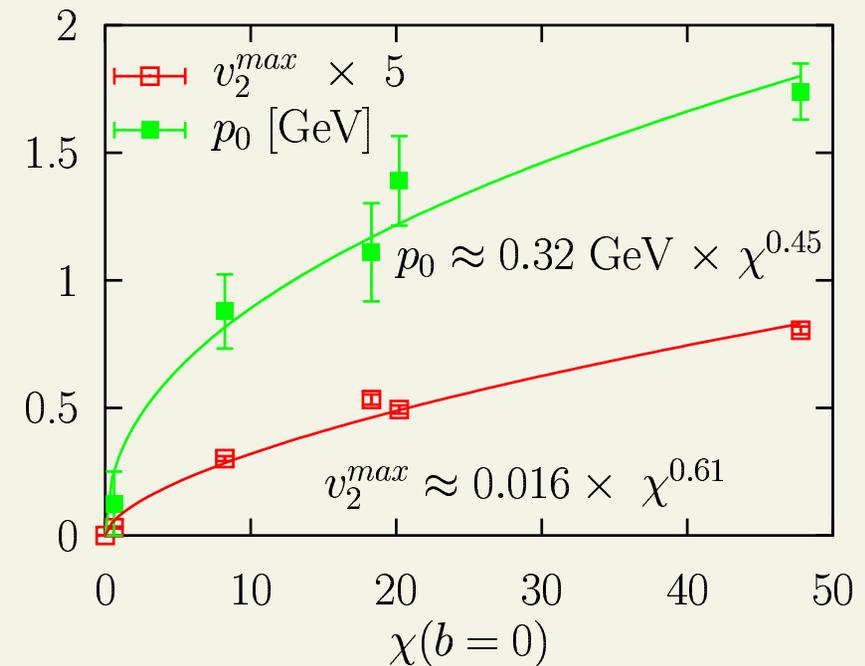
Au+Au @ 130 GeV, $b = 8$ fm from covariant transport

DM & Gyulassy, NPA 697 ('02): $v_2(p_T, \chi)$



nonlinear opacity dependence

$$v_2(p_T, \chi) \approx v_2^{max}(\chi) \tanh(p_T/p_0(\chi))$$

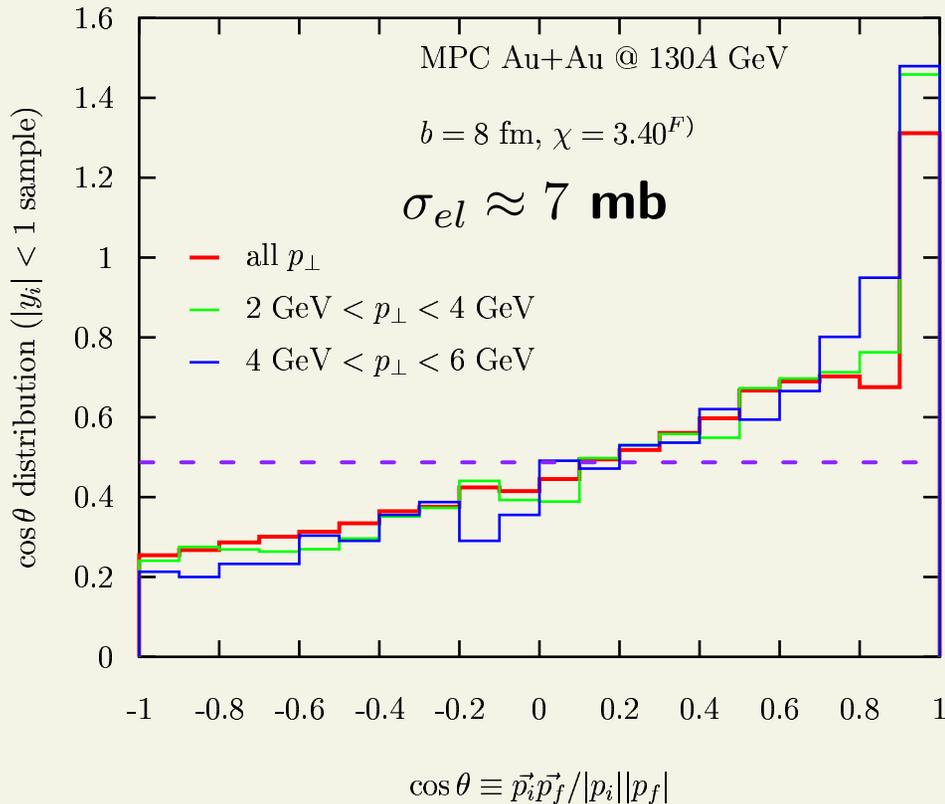


super-opaque plasma - $15 \times$ perturbative opacities, $N_{coll}(b=0) \sim 70$, $\lambda_{MFP} \sim 0.1$ fm

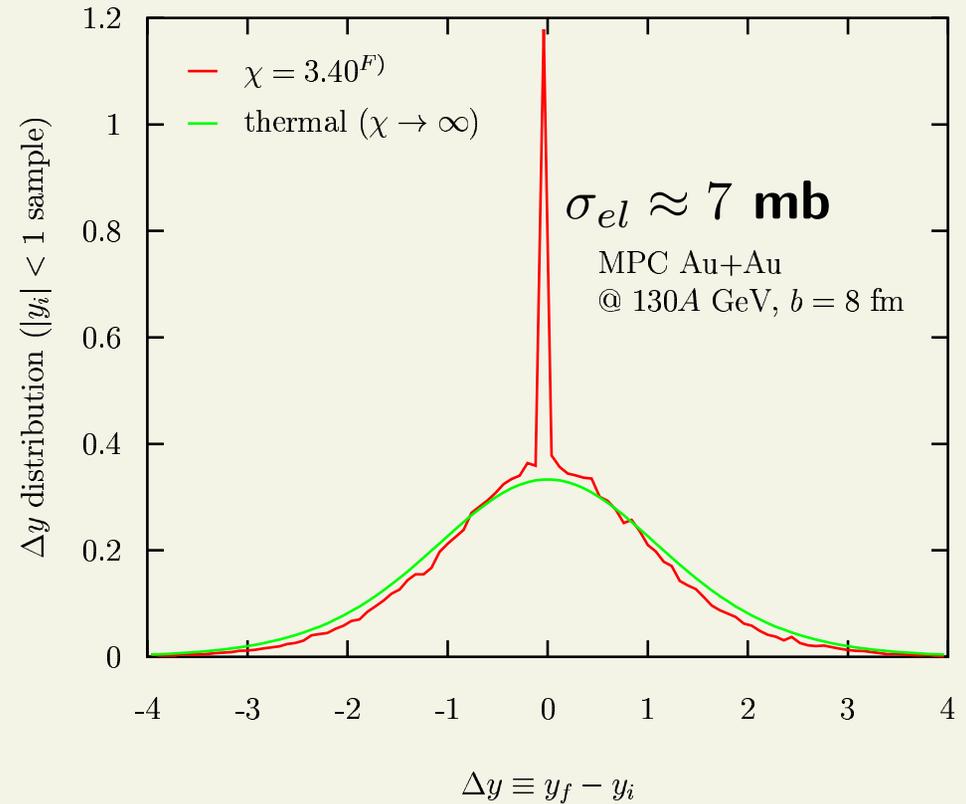
(saturated gluon $\frac{dN^{cent}}{d\eta} = 1000$, $T_{eff} \approx 0.7$ GeV, $\tau_0 = 0.1$ fm, 1 parton \rightarrow 1 π hadr.)

Significant randomization

a) deflection angle $\vec{p}_i \angle \vec{p}_f$



b) rapidity shift $y_f - y_i$



light parton momenta randomize to large degree, already for $\sigma \sim 7 \text{ mb}$ ($\chi \sim 7$)

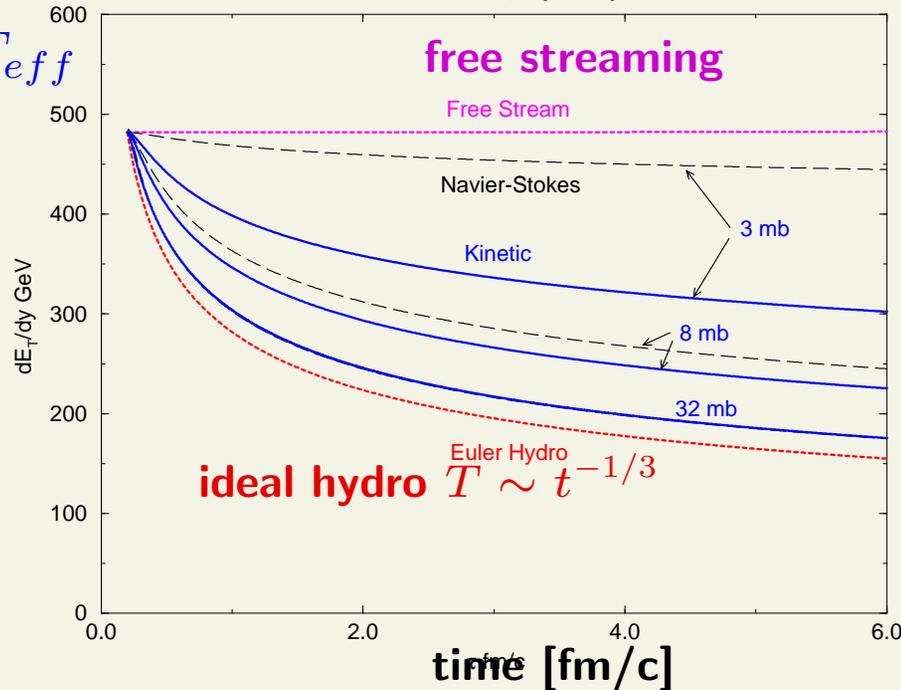
Still not ideal fluid(!)

Even $\sigma_{gg \rightarrow gg} \sim 50 \text{ mb}$ is insufficient for ideal hydro (perturbative QGP: $\sim 3 \text{ mb}$)

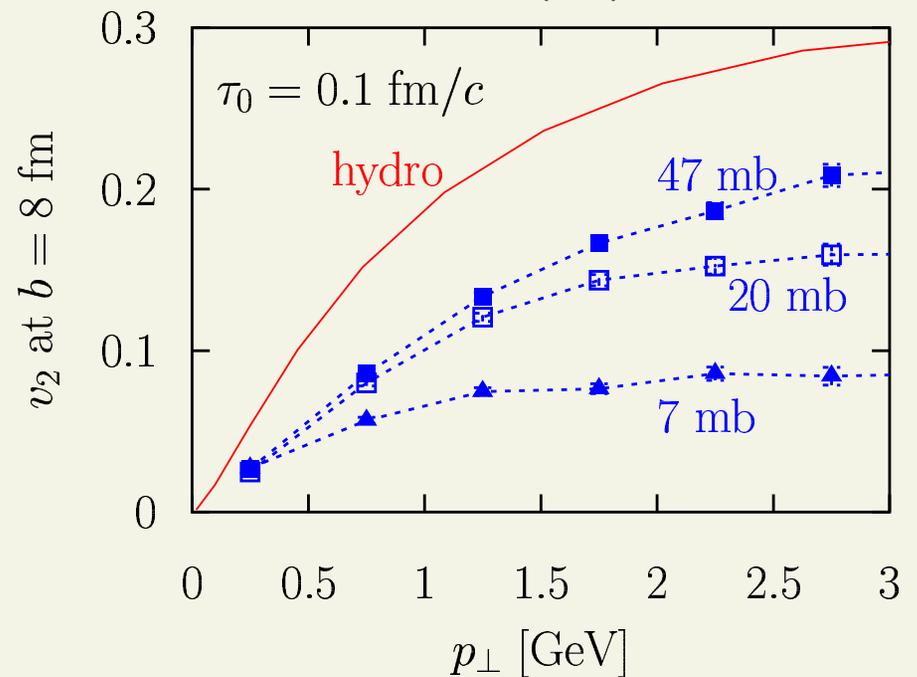
- less pdV work, slower cooling

- dissipation reduces v_2 by 30–50%

Gyulassy, Pang & Zhang ('97): 1+1D



DM & Huovinen, PRL94 ('05): 3+1D



→ dense, strongly-interacting system, but dissipative

very short mean free path $\lambda \sim 0.1 \text{ fm}$ - close to uncertainty bound $\lambda T \gtrsim 1/5$

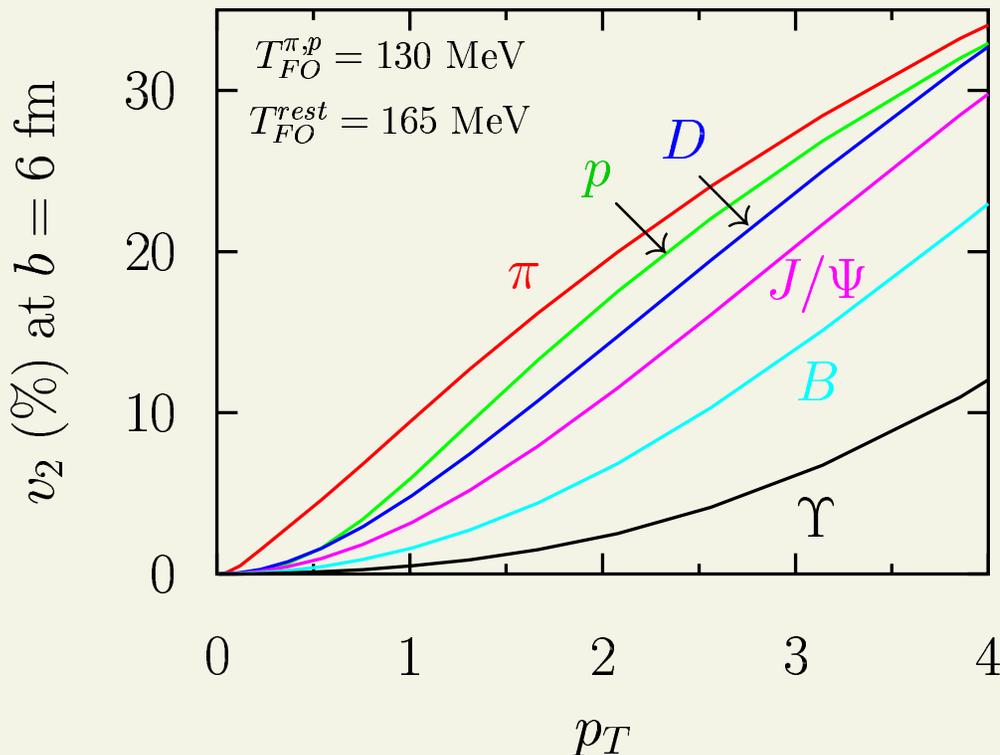
Gyulassy, Danielewicz '85

Results for charm at RHIC

Ideal hydro benchmark

hydro **not** expected to apply to heavy quarks... but still a **useful baseline**
- very likely an upper limit

Huovinen ('04, priv. comm.): **quick estimate for Au+Au @ RHIC, $b = 6$ fm**



assumes:

- chem. equilibrium **also for c & b**
- no hadronic interactions for c & b
should be ok for open charm/bottom
- no resonance contributions for c & b

too naive for J/Ψ & Υ

hydro mass hierarchy simply extends to heavy flavor

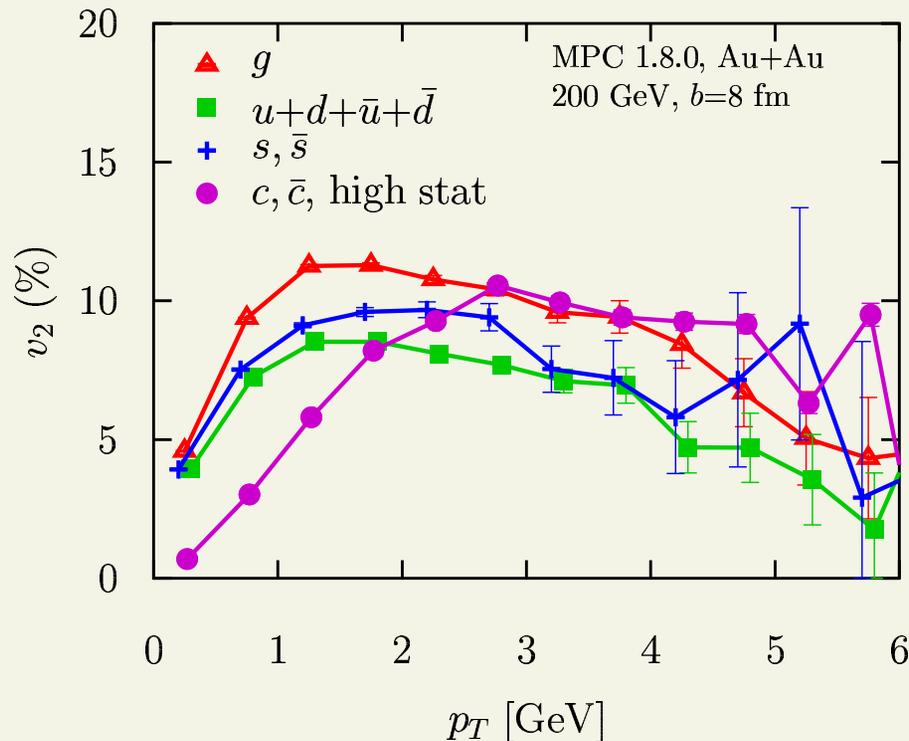
quite large charm/bottom v_2 's for early freezeout - much smaller if $T_{FO} = 130$ MeV

Charm v_2 from transport theory

Most efficient $2 \rightarrow 2$ process: $gc \rightarrow gc$ $\frac{d\sigma_{gc \rightarrow gc}}{dt} \sim \frac{2\pi\alpha_s^2}{(t-\mu_D)^2} + \dots$

average mom. transfer: $\Delta q^2 \sim \mu_D^2 \ln \frac{6ET}{\mu_D^2(1+M^2/6ET)}$

DM ('04):



Au+Au @ 200GeV, $b = 8$ fm

from MPC 1.8.0 w/ elastic & inelastic $2 \rightarrow 2$

$\sigma_{gg \rightarrow gg} = 10$ mb

($\mu_D = 0.7$ GeV, $m_c = 1.2$ GeV, pQCD + saturation
initconds, $\frac{dN^{parton}}{d\eta}(b=0) = 2000$)

- **charm should flow** - above $p_T \approx 2.5 - 3$ GeV same v_2 as light partons
- **at low p_T charm v_2 rises slower** \sim resembles the hydro mass effect

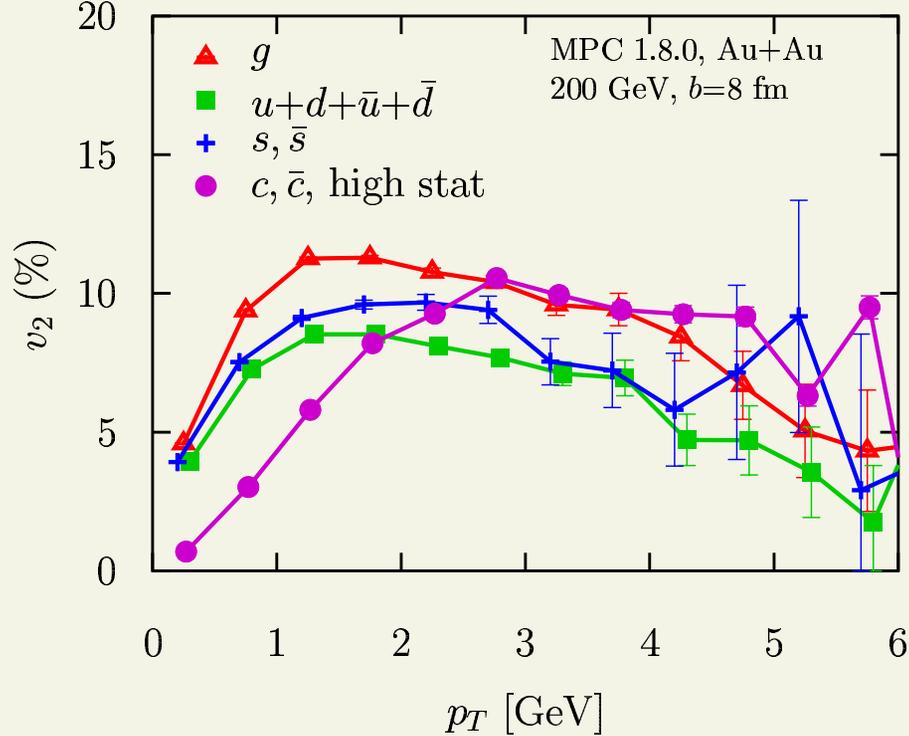
Prelim. data indicate charm flow

parton transport MPC 1.8.0

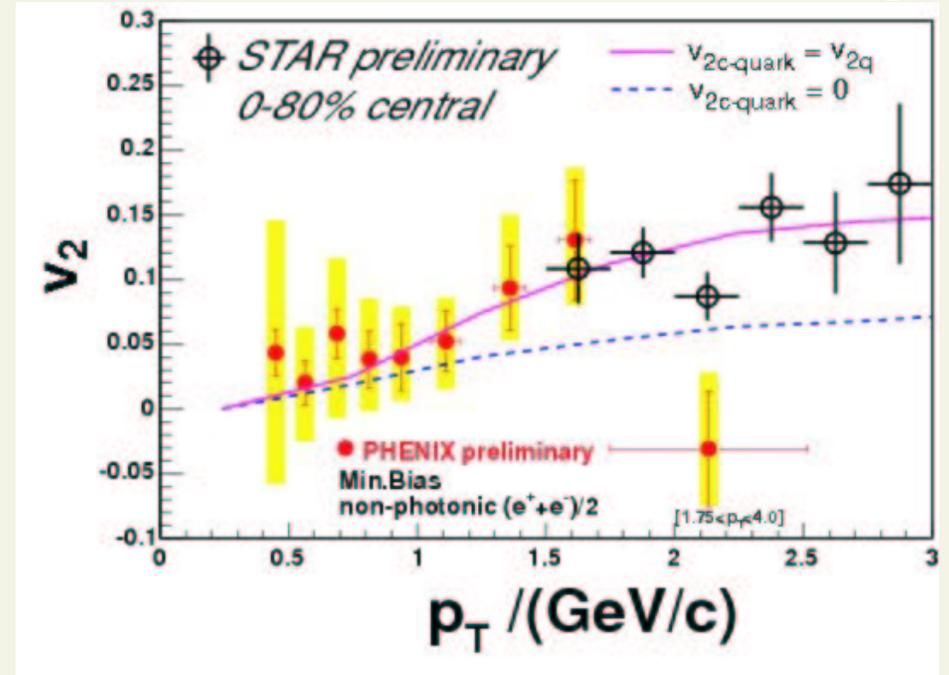
vs

indirect $D(qc)$ meson measurement:

DM, JPG ('04): **parton** v_2



PHENIX, STAR ('04): **decay electron** $v_2 \approx v_2^D$



elastic & inel. $2 \rightarrow 2$

$6 \times$ perturbative opacities

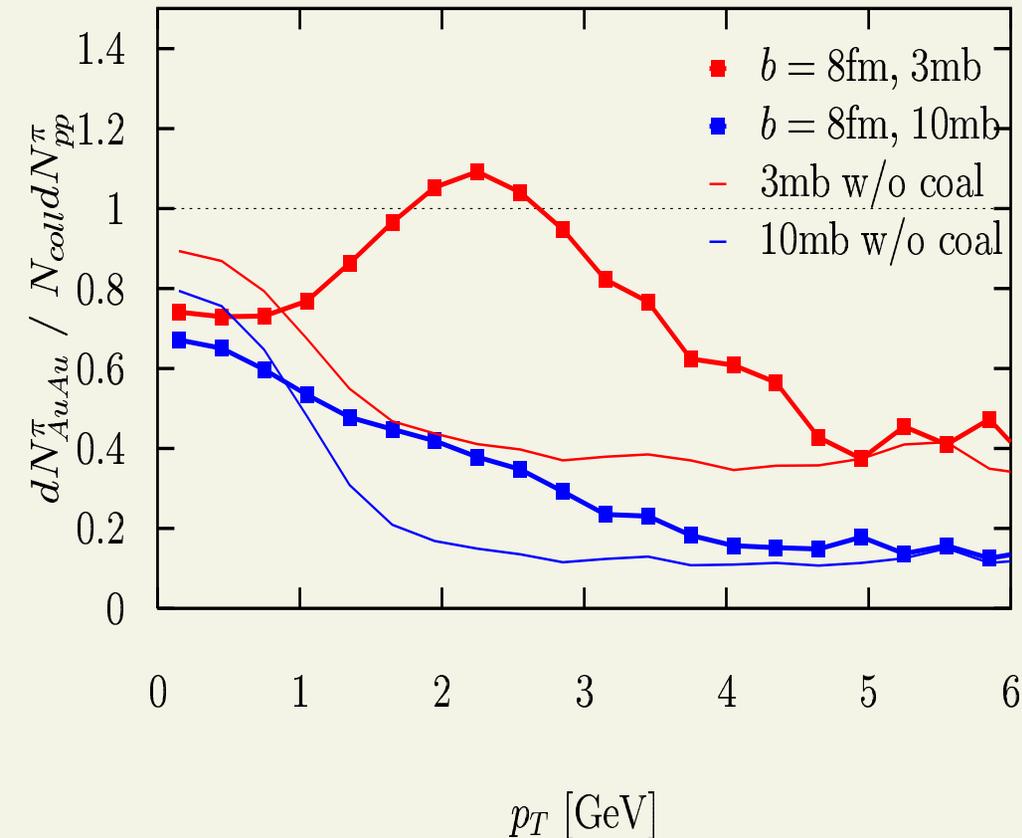
qualitative agreement, now detailed studies needed - $v_2(b, \chi, \sqrt{s})$

uses decay electrons: $D \rightarrow K^{(*)} \nu e$

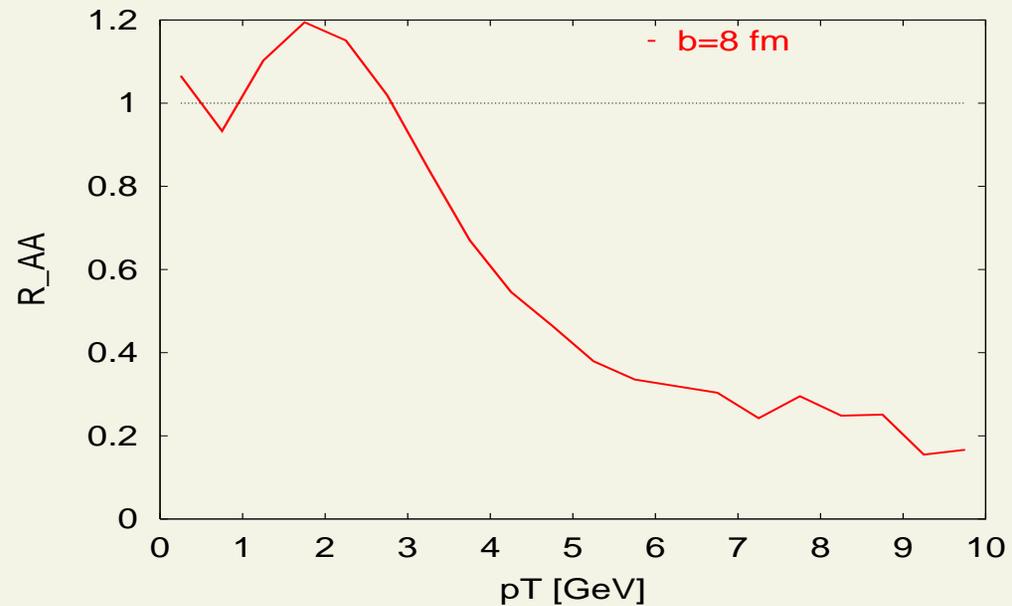
e's from hadron decays and γ -conversion subtracted
 \equiv "non-photonic"

Charm R_{AA}

DM '04: **light** R_{AA} thin: frag, thick: coal+frag



DM '04: **charm** $R_{AA}, \sigma_{gg} = 10 \text{ mb}$

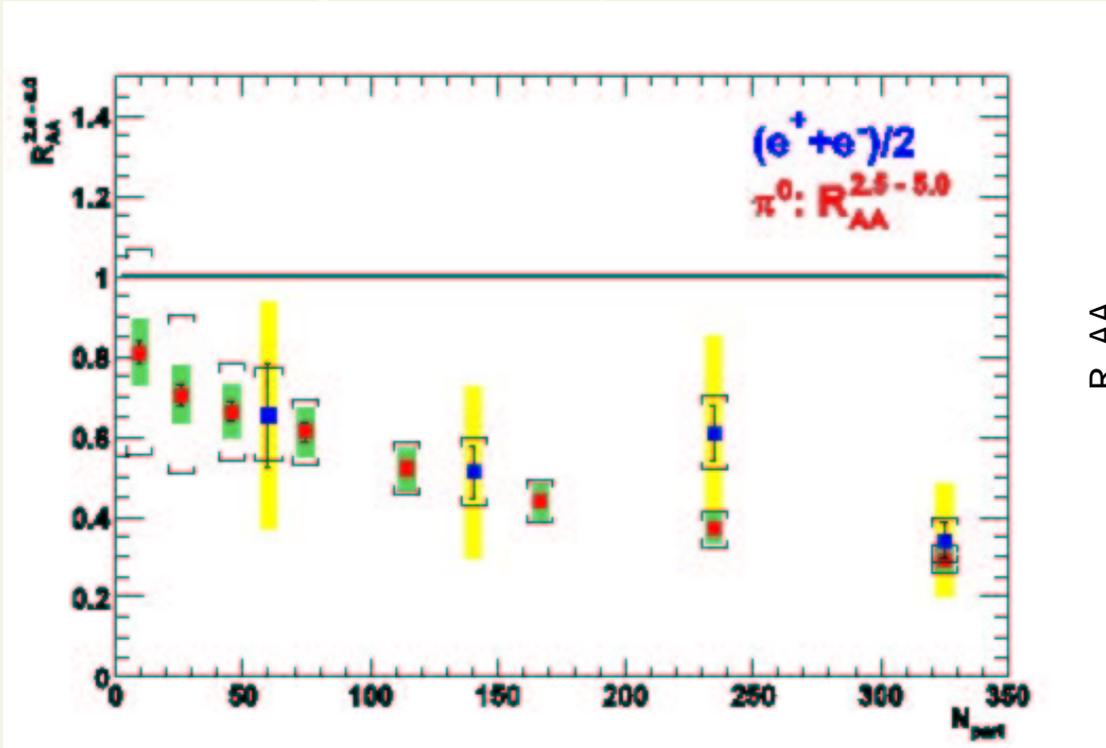


charm R_{AA} above light R_{AA} even at $p_T \sim 10 \text{ GeV}$ - as expected

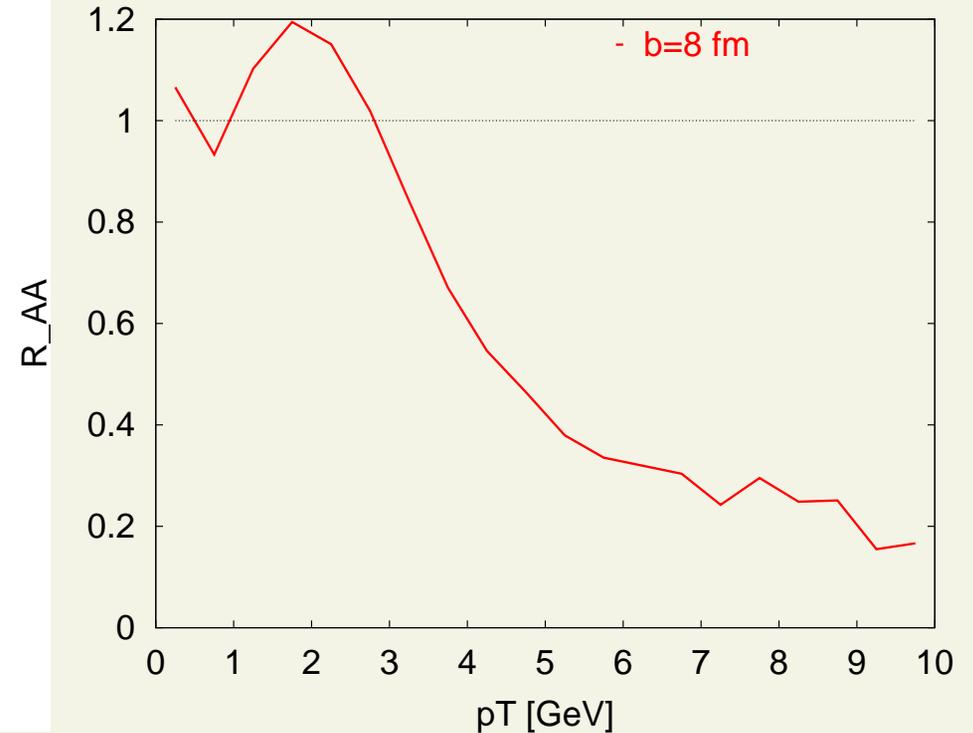
charm R_{AA} decreases slowly whereas light R_{AA} nearly flat

Comparison to **prelim.** RHIC data

PHENIX '05: **light vs heavy** R_{AA}



DM '04:



data show little difference between light and heavy flavor (for $p_T > 2 - 2.5$ GeV)

agreement for charm looks better (light $R_{AA} < 0.2$ too low from transport)

radial flow peak near $p_T \sim 2$ GeV for charm

Langevin dynamics

Teaney & Arnold '04

an approximation to full Boltzmann

collision term $C[f]$ replaced with drag + random Gaussian noise

correct average and variance of mom. transfer, but not tails (fluctuations)

$$\frac{d\vec{p}}{dt} = -\eta_D \vec{p} + \vec{\xi}(t) , \quad \langle \xi_i(t) \xi_j(t') \rangle = \kappa \delta_{ij} \delta(t - t')$$

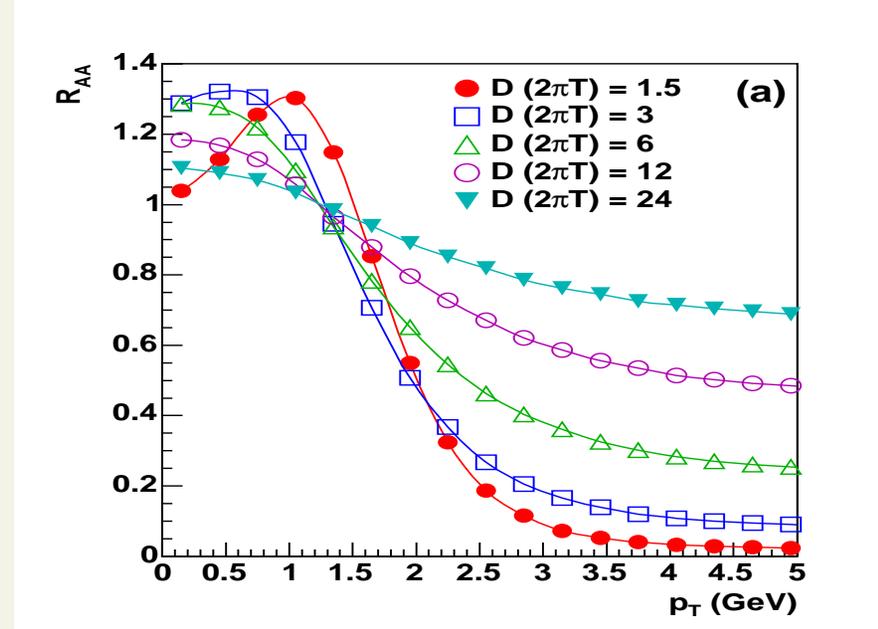
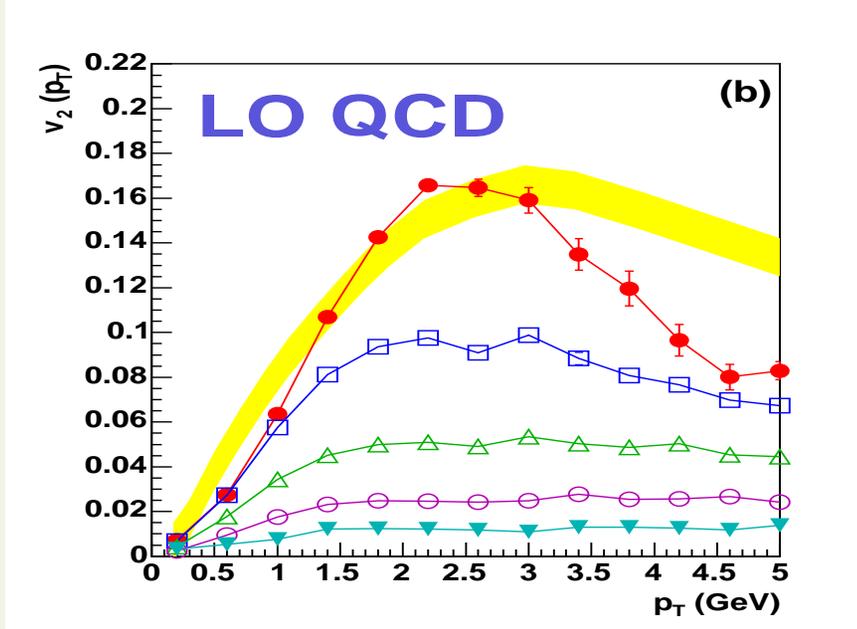
long-time behavior:

$$\langle \vec{p}(t) \vec{p}(t) \rangle = 3MT \Leftrightarrow \kappa = M T \eta_D, \quad 6Dt \equiv \langle \vec{x}(t) \vec{x}(t) \rangle = \frac{6Tt}{M\eta_D}$$

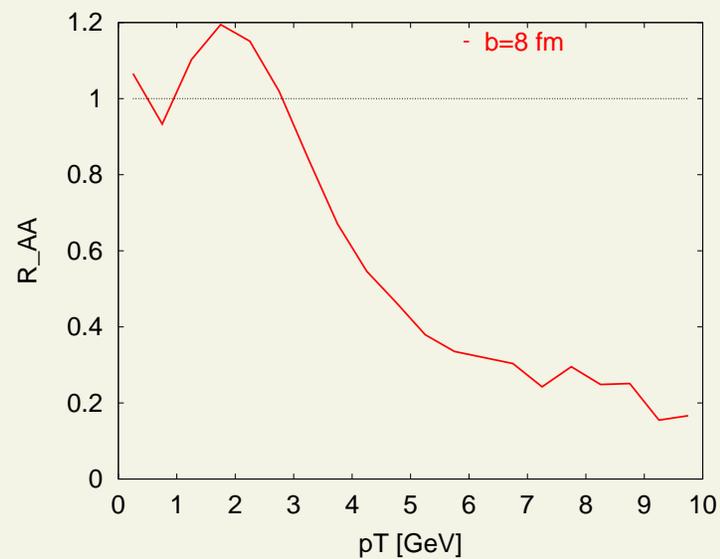
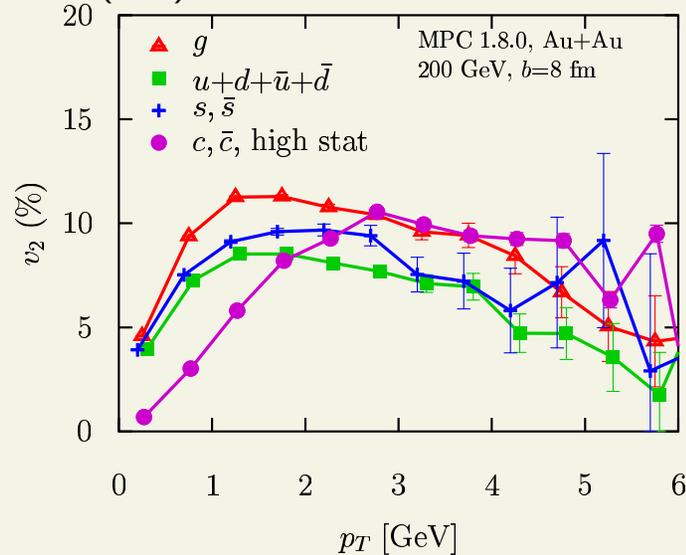
\Rightarrow diffusion D , drag η_D , noise κ - all equivalent

qualitatively similar to Boltzmann - but quantitative differences $D \sim 1/\sigma_{tr}$

Teaney, Arnold ('04):



DM ('04)



Langevin: flow peak at lower p_T & stronger high- p_T suppression

Open issues

- secondary (thermal) charm
- hadronization (coalescence)
- coherence effects

assume: all $2 \rightarrow 2$ processes are enhanced by **same factor** in opaque plasma

based on Cambridge NPB 151 ('79) 429:

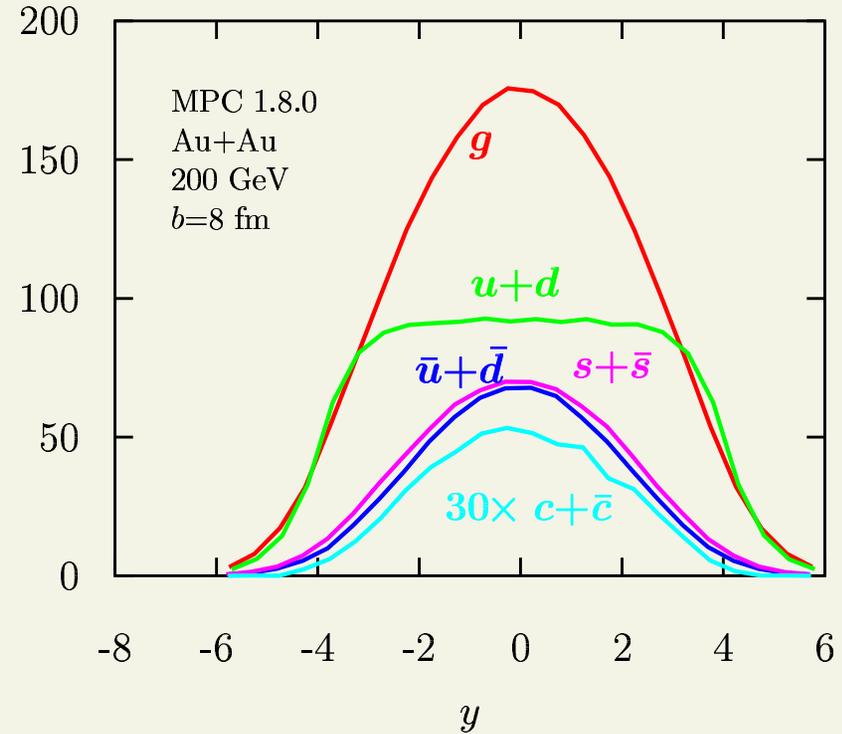
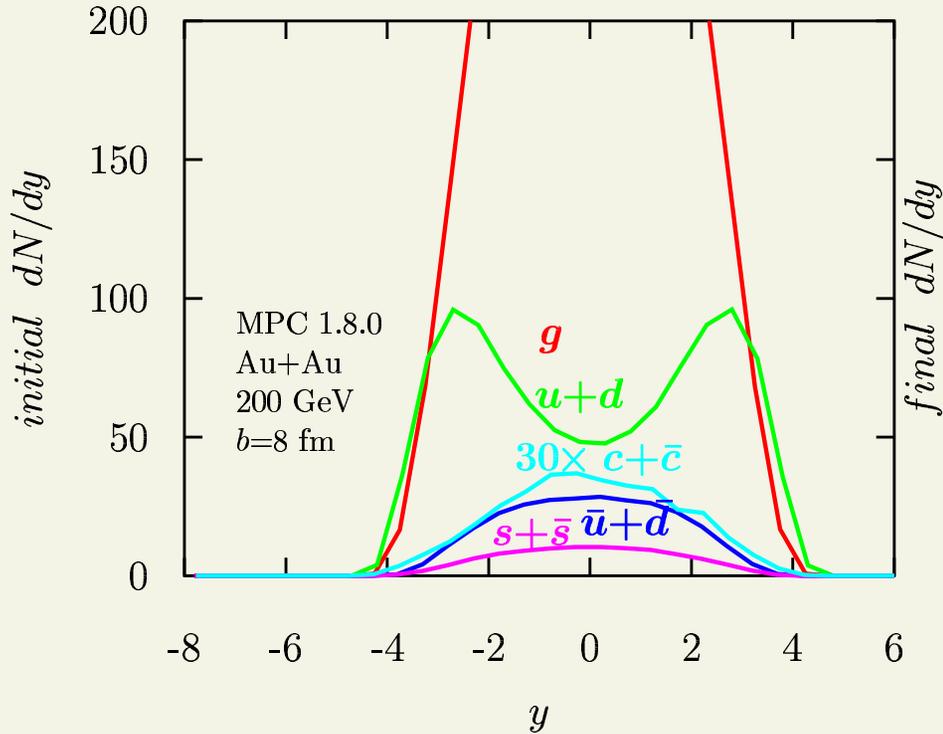
$$\begin{aligned}
 \sigma_{gg \rightarrow q\bar{q}} &= \frac{2r}{27} \frac{1+r}{1+2r} \ln\left(1 + \frac{1}{r}\right) \sigma_{gg \rightarrow gg} \quad , \quad \sigma_{q_i \bar{q}_i \rightarrow q_j \bar{q}_j} = \frac{16r}{243} \sigma_{gg \rightarrow gg} \\
 \sigma_{gg \rightarrow c\bar{c}} &= \frac{2r}{27} \Theta(1-4R) \left[(1+4R+R^2) \ln \frac{1+\sqrt{1-4R}}{1-\sqrt{1-4R}} - (7+3R) \frac{\sqrt{1-4R}}{4} \right] \sigma_{gg \rightarrow gg} \\
 \sigma_{q\bar{q} \rightarrow c\bar{c}} &= \frac{16r}{243} \Theta(1-4R) (1+2R) \sqrt{1-4R} \sigma_{gg \rightarrow gg}
 \end{aligned}$$

where $r \equiv \mu_D^2/s$, $R \equiv M_c^2/s$

take $\mu_D = 0.7$ GeV, $M_c = 1.2$ GeV

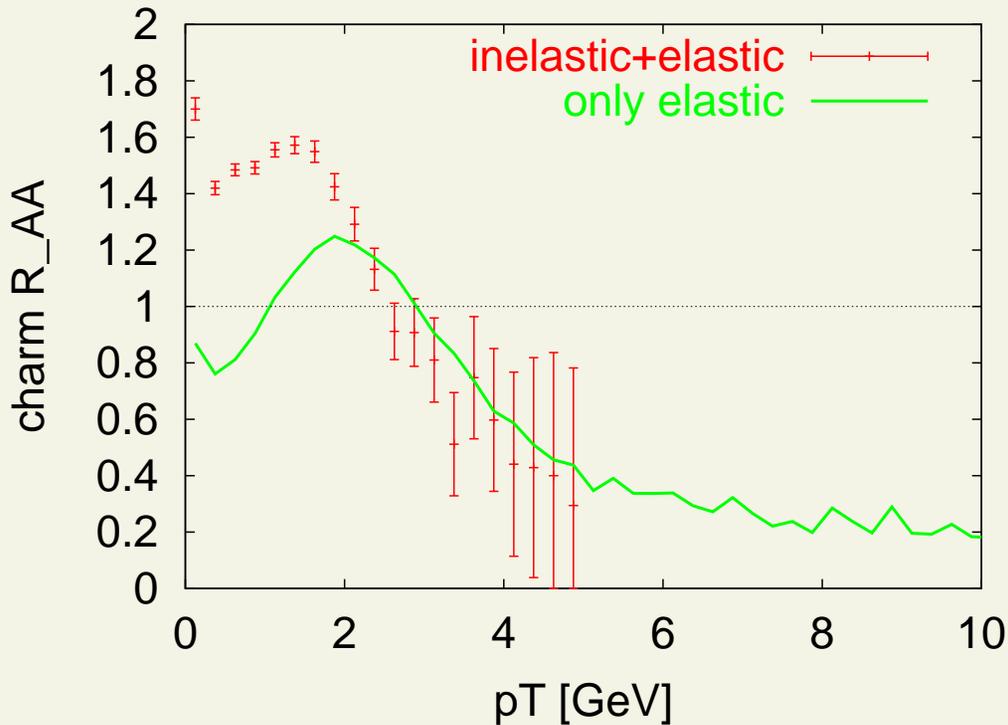
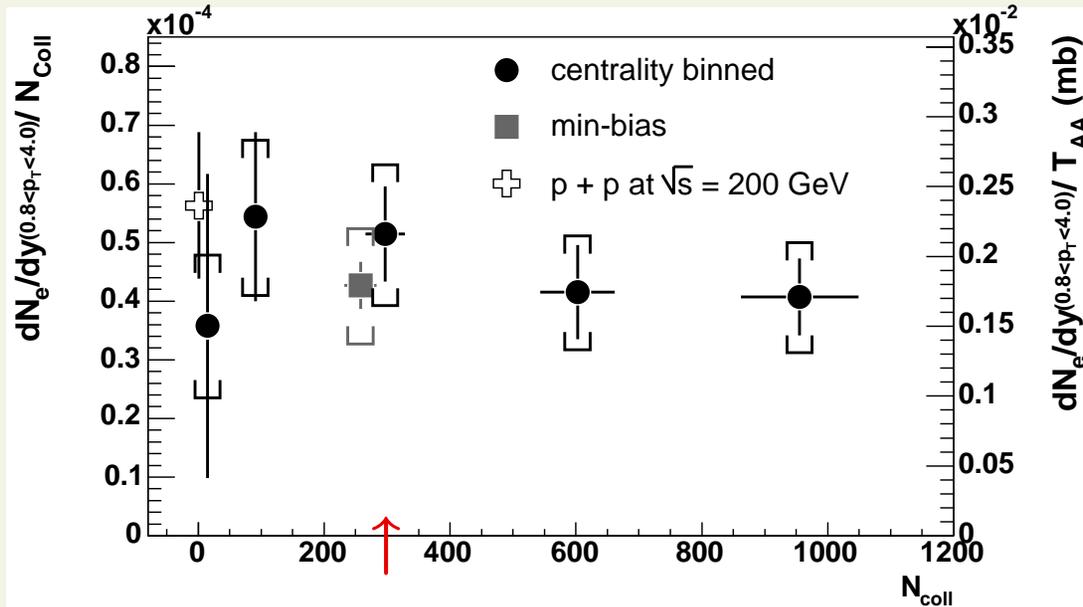
DM, JPG ('04): **significant secondary charm production**

initial dN/dy vs. **final rapidity distr.** R_{AA}



half the glue fuse to $q\bar{q}$, strangeness up $5\times$, also extra 40 – 50% charm yield

BUT: data PHENIX, PRL94 '05 - no secondary charm (collision scaling)



← transport: secondary charm at low-pT
 from gluon fusion $gg \rightarrow c\bar{c}$

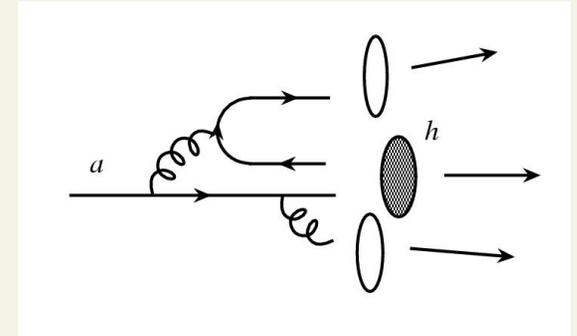
Influence of hadronization

- **hadronization in equilibrium:** → hydrodynamic v_2 results apply

- **independent fragmentation:** $D_{a \rightarrow h}(z) \rightarrow$

collinear approx. - $v_2^{hadron}(z p_T) \approx v_2^{parton}(p_T)$

for heavy quarks - $z \approx 1$ strongly preferred

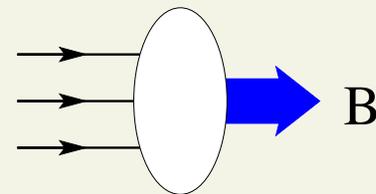
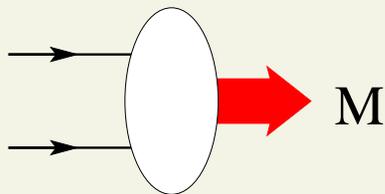


⇒ **high p_T :** heavy flavor v_2 reflects heavy quark v_2

- **parton coalescence**

Hwa, Yang, Biró, Zimányi, Lévai, Csizmadia, Ko, Lin, Voloshin, DM, Greco, Fries, Müller, Nonaka, Bass, ...

at lower and intermed. p_T - large parton density ⇒ multi-parton processes **also** relevant



lowest-order $q\bar{q} \rightarrow M$, $qqq \rightarrow B$ (valence quarks only)

(!) **flow amplification:** $v_2^{hadron}(p_T) \approx \sum_i v_2^{quark,i}(p_{T,i})$

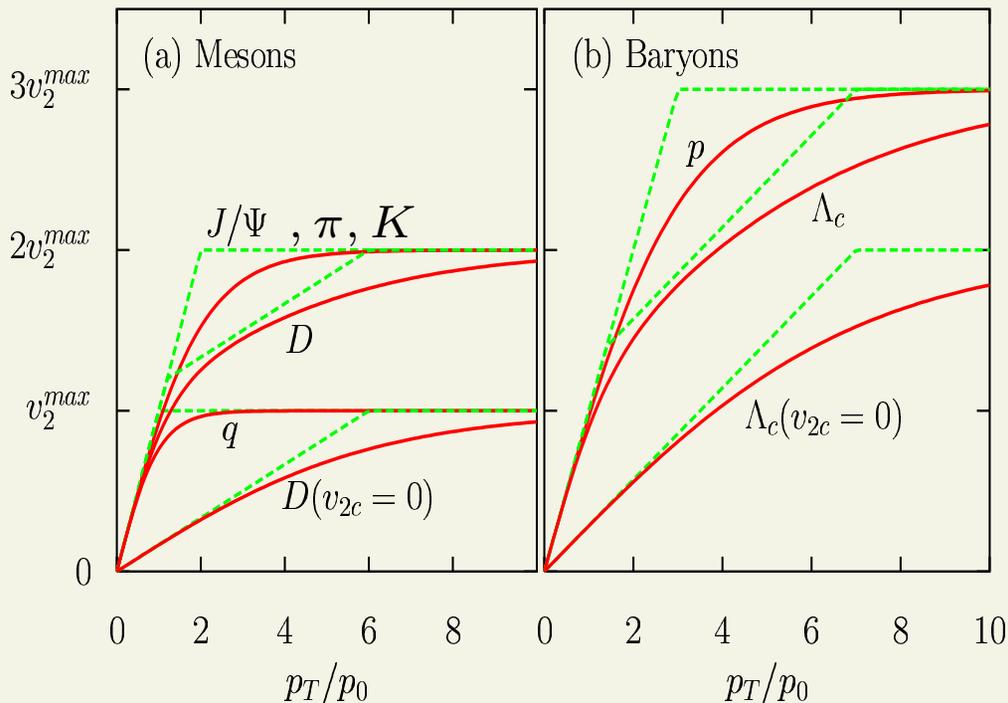
$$p_{T,i} \approx p_T \cdot m_i / m_h$$

Voloshin, DM ('03)

Lin, DM ('03)

Charm hadron v_2 from coalescence

generic features: Lin & DM ('03)



two scenarios: $v_2^{charm} = 0$ or $v_2^{charm} = v_2^{light}$

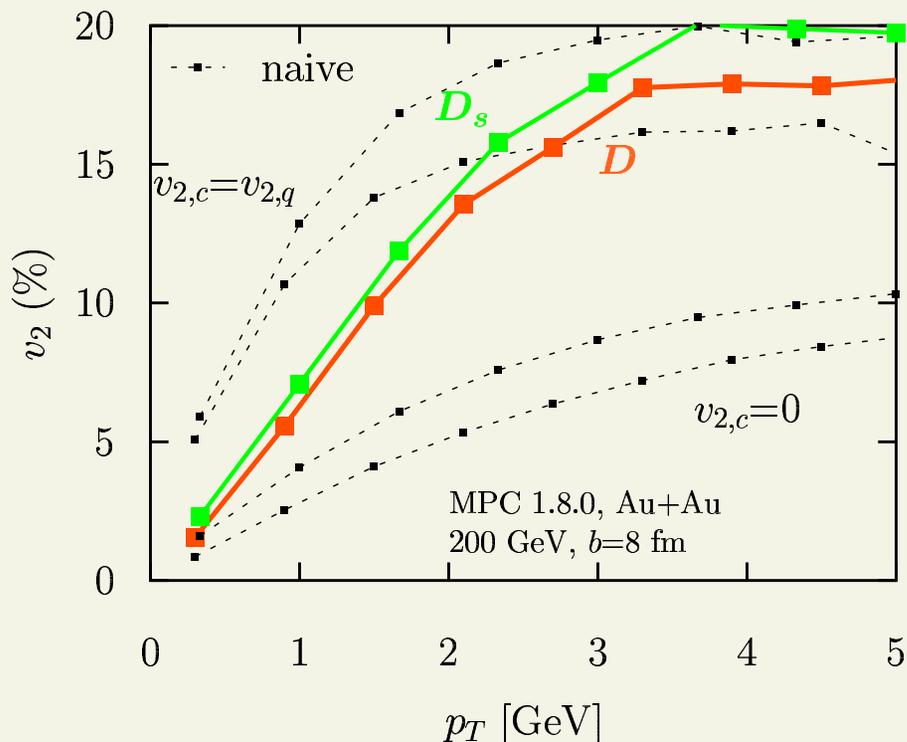
$v_2(p_\perp)$ rises slower, saturates later for asymmetric systems (D , D_s , Λ_c)

- heavy quark carries most of hadron momentum

D , D_s , Λ_c all flow even if charm does not

- "inherit" the light quark flow

cov. transport theory (MPC): DM ('04)



note: charm quarks do flow in this model

D saturates at $p_T \sim 3$ GeV, later than light mesons ($p_T \sim 2$ GeV)

- very different from scenario w/o charm flow

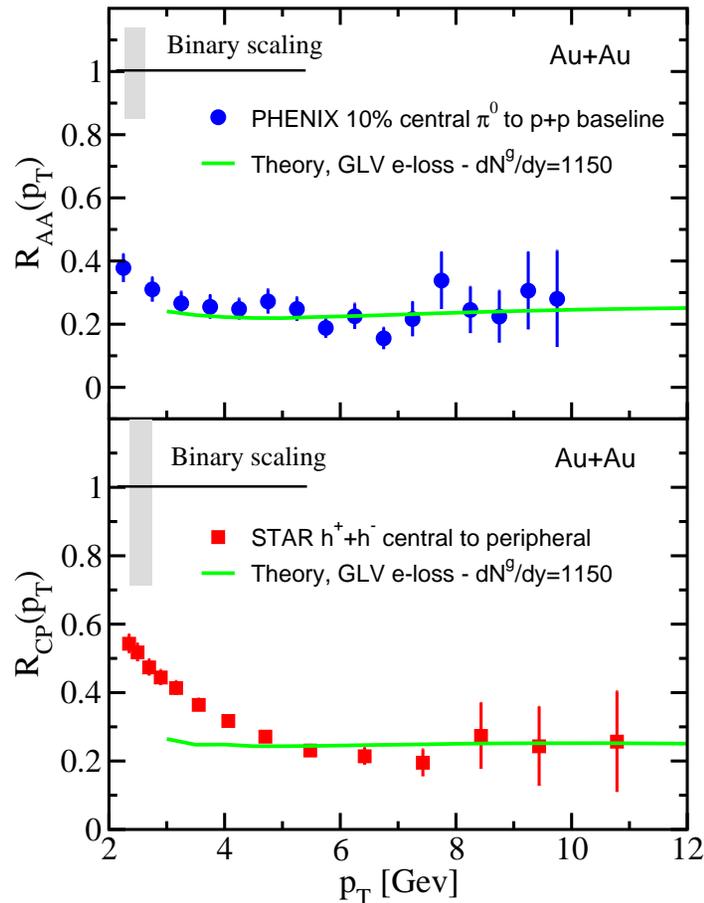
saturation still at $2 \times$ quark v_2 maximum from simple coal approach

Alternative: coherent energy loss

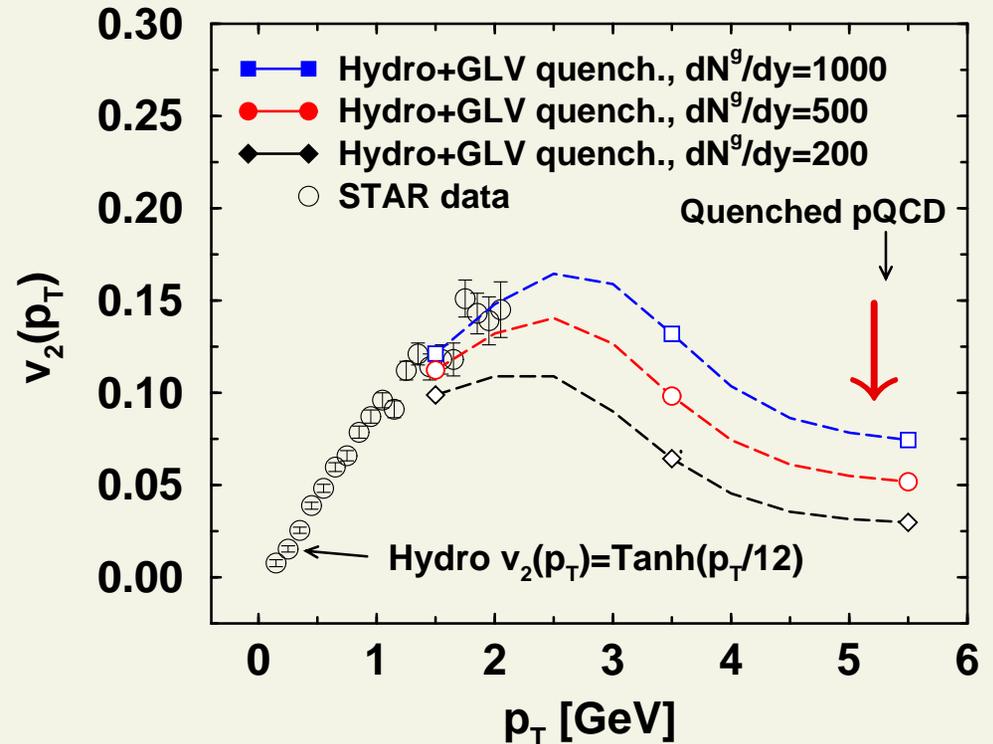
Gyulassy, Vitev, Wang et al, Dokshitzer et al, Wiedemann, Salgado et al ...

modest opacities, coherent inelastic interactions, $N_{coll}(b=0) \sim 5$, $\lambda_{MFP} \sim 1\text{fm}$
 - $dN^{glue}/d\eta \sim 1100$, perturbative cross sections - **no thermalization**

Vitev, QM2004: GLV approach



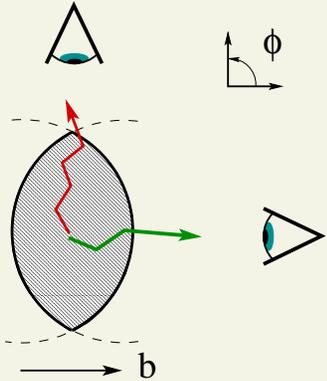
Gyulassy, Vitev, PRL86 '01:



reality may lie between coherent and incoherent limits \Rightarrow should study both

Coherence is important

how to get large v_2 with modest opacity



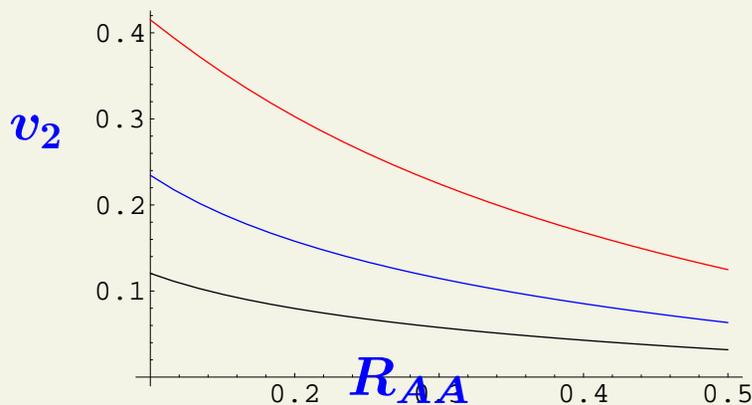
$$\frac{1 - 2v_2}{1 + 2v_2} \approx \frac{R_{AA}(\phi = 90^\circ)}{R_{AA}(\phi = 0)} \Rightarrow \text{need strong length dependence}$$

incoh. multiple scatterings: $\Delta E \propto L$ (static), **expect** $\Delta E \propto \log(L)$ (Bjorken)

non-Abelian gluon radiation: $\Delta E \propto L^2$ (static), $\Delta E \propto L$ (Bjorken)

DM '05

1



v_2 vs R_{AA} at $b = 8$ fm:

$\Delta E \propto L^2$ (static), $\propto L$ (Bjorken)

$\Delta E \propto L^{3/2}$ (static), $\propto L^{1/2}$ (Bjorken)

$\Delta E \propto L^{5/4}$ (static), $\propto L^{1/4}$ (Bjorken)

\Rightarrow **should add coherence effects into transport (none at present)**

Heavy quark energy loss

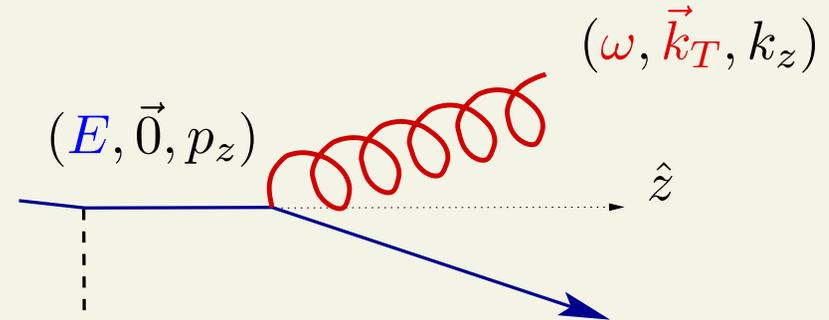
Dokshitzer, Kharzeev, Gyulassy, Djordjevic, Wiedemann, Salgado, ...

Heavy quarks radiate **less energy**.

- **suppression of vacuum radiation:**

$$\text{massless } q: \frac{dN_g}{d\omega dk_T^2} = \frac{4\alpha_s}{3\pi} \frac{1}{\omega k_T^2}$$

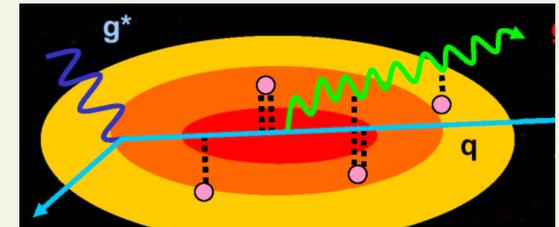
$$\text{massive } q: \frac{dN_g}{d\omega dk_T^2} = \frac{4\alpha_s}{3\pi} \frac{k_T^2}{\omega(k_T^2 + \omega^2 M^2/E^2)^2}$$



most reduction at small angles $\theta \approx k_T/\omega < \sim M/E \rightarrow$ **dead cone**

- **similar expectation for medium induced radiation**

\rightarrow in medium also: **LPM suppression, massive quanta, transition radiation...**

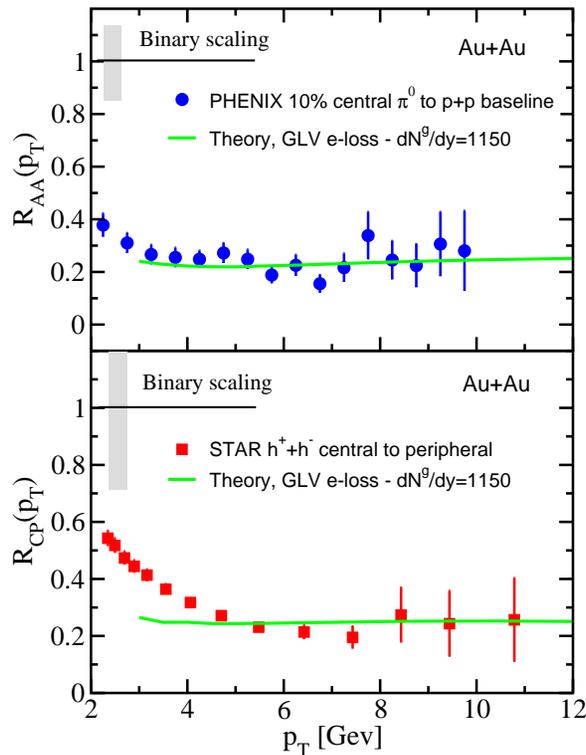


- **reduction is also there in classical electrodynamics:**

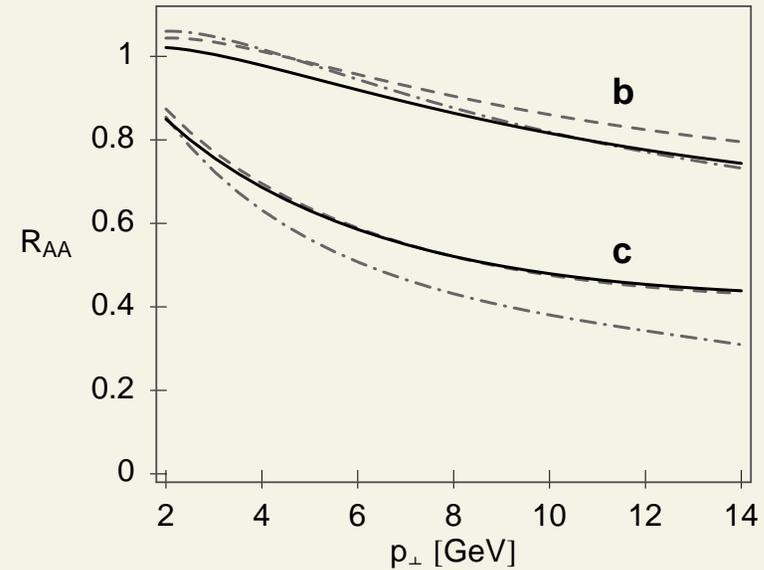
$$\text{radiated energy: } \frac{dE}{dt} = - \frac{2e^2}{3M^2} \left(\frac{dp_\mu}{d\tau} \frac{dp^\mu}{d\tau} \right)$$

under same **momentum transfers**, heavy particle radiates less

Vitev @ QM2004: **light g,q**

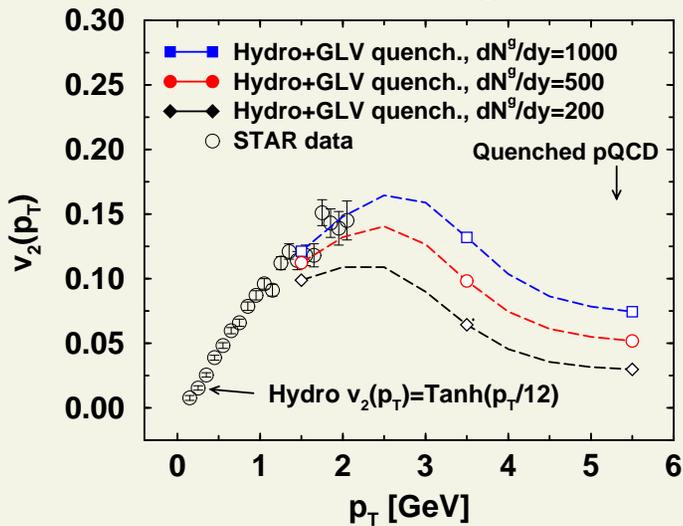


Djordjevic, Gyulassy, Wick '04: **heavy c,b**



⇒ **DGLV: much weaker high-pT suppr.**
disagrees w/ Salgado et al...

Gyulassy, Vitev '01: **light v2 ~ 7%**



DM @ SQM2004, estimate:

heavy-q v2 ~ 20% below light hadron v2

$$\frac{1 - 2v_2}{1 + 2v_2} \approx \frac{R_{AA}(\phi = 90^\circ)}{R_{AA}(\phi = 0)} \Rightarrow v_2^{\text{charm}} \sim 5 - 6\%$$

$$(\Delta E/E(0) \approx 0.36, \Delta E/E(90^\circ) \approx 0.42)$$

fluctuations in $\Delta E \rightarrow$ use $0.5\langle\Delta E\rangle \equiv \delta$

power law $\frac{dN}{dp_T} \sim p_T^{-\alpha} \Rightarrow R_{AA} \approx (1 - \delta)^{\alpha-1}$, take $\alpha = 7$

Summary

- Covariant transport theory is one of the few frameworks we have to study equilibration. Light-sector observables at RHIC indicate super-opaque, largely randomized, but **still dissipative plasma** ($N_{coll}(b=0) \sim 70$, $\lambda_{MFP} \sim 0.1\text{fm}$).
- Such conditions (should) generate **significant charm elliptic flow that, above $p_T \sim 2.5 - 3$ GeV is similar to light parton v_2** . On the other hand, a weaker high-pT suppression is expected for charm, even at $p_T \sim 10$ GeV.

Similar results were found within the Langevin approx. Teaney, Arnold '04.

- **Several puzzles/issues remain:**
 - predict **secondary charm** but none observed
 - **coherence effects** lacking \rightarrow may reduce opacity estimates significantly
transport light hadron R_{AA} too low, better for charm - coh. E-loss results vary wildly
Djordjevic et al vs Salgado et al
 - **hadronization** uncertainties (coalescence or frag, dynamics?)
 - electron measurements - contributions from **bottom**
 - even charm yield in **p+p** is not understood Vogt et al